Latest Research Developments by the National Renewable Energy Laboratory - Part 3

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This course was adapted from the National Renewable Energy Laboratory (NREL), "Recent Developments in Renewable Energy Research at NREL Part 3", which is in the public domain.

Recent Developments in Renewable Energy Research at NREL Part 3

Introduction. The National Renewable Energy Laboratory (NREL) is the U.S. Department of Energy's primary national laboratory for renewable energy and energy efficiency research and development. NREL is operated for the Energy Department by the Alliance for Sustainable Energy LLC, a partnership between Battelle and MRIGlobal.

NREL's mission is to advance the science and engineering of energy efficiency, sustainable transportation, and renewable power technologies and provide the knowledge to integrate and optimize energy systems.

Every year in addition to publishing technical articles and reports, NREL publishes dozens of NREL News & Feature Stories that take an in-depth, behind-the-scenes look at the latest news and research breakthroughs.

The present course is Part 3 of a three-part series of courses based on excerpts of recently published News & Feature Stories. In general, all three courses should be of interest to anyone wanting to keep up with recent developments from a laboratory regularly recognized for national and global leadership in energy efficiency and renewable energy research and development.

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Chapter 1. On the Road to 100% Clean Electricity: Six Potential Strategies To Break Through Last Few Percent

Study Surveys Trade-Offs of Technology Options To Overcome Challenging Last Few Percent to Zero-Emissions U.S. Power Grid

Sept. 12, 2022 | By Madeline Geocaris

A growing body of research has demonstrated that cost-effective high-renewable power systems are possible, but costs increase as systems approach 100% carbon-free electricity—what has become known as the "last 10% problem."

The increase in costs is largely driven by a seasonal mismatch between the timing of variable renewable energy generation and demand. Meeting peak demand is challenging and expensive for all power systems, but addressing the seasonal mismatch issue for high-renewable power systems may require technologies that have yet to be deployed at a large scale. That makes their costs and requirements unclear.

To help move toward potential solutions for this challenge, a team of National Renewable Energy Laboratory (NREL) researchers studied trade-offs of six possible technology strategies to get from 90% to 100% carbon-free electricity in the United States. This work, funded by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, is published in a *Joule* article and can help inform decision-making today.

"None of the strategies are perfect, and a lot of uncertainty remains, but the study highlights key challenges with the last 10% and examines all the major technology options," said Trieu Mai, NREL analyst and lead author of the study. "More research and development will be important to move closer to a clear solution for the last 10% and progress the United States toward a decarbonized power sector."

What We Know So Far About the Last 10% Challenge

NREL has been studying a variety of questions related to achieving 100% renewable generation in the United States.

In a previous *Joule* article, NREL outlined the techno-economic challenges of achieving 100% renewables across all timescales. The study explored two types of challenges: one related to economically maintaining a balance of supply and demand and another challenge related to designing technically reliable and stable grids using largely inverter-based resources like wind and solar.

In a follow-on study, NREL used state-of-the-art modeling capabilities to understand possible pathways and system costs of transitioning to a 100% renewable power grid. Results, published in another *Joule* article, show that costs are significantly lower if there is a cost-effective source of firm capacity—resources that can provide energy during periods of lower wind and solar generation, extremely high demand, and unplanned events like transmission line outages. Other resources besides wind, solar, and diurnal storage or load flexibility could be important for overcoming the last few percent to a 100% renewable power grid.

In the Los Angeles 100% Renewable Energy Study (LA100), NREL used multiple models to examine which resources could be used to help meet the last 10% and maintain reliability for the city of Los Angeles. NREL also recently completed a landmark study on achieving 100% carbon-free electricity by 2035. The analysis shows there are multiple pathways to achieve the goal in which the environmental and societal benefits exceed the costs.

This latest *Joule* article builds on the NREL high-renewable-generation power grid studies by exploring trade-offs of potential technical solutions that could be implemented for the last few percent.

Six Strategies for the Last 10%

The ideal technology solution for the last 10% has three primary characteristics. First, the ideal solution has high capacity credit so that capacity is available during high-stress periods and can support resource adequacy—one of the "three Rs of power system reliability" that must be successful for a safe and reliable power system. Second, the ideal solution has relatively low capital costs because it will not be used often. And third, it relies on broadly available resources and can be deployed at scale. NREL surveyed six technology strategies that have the potential to meet the three primary characteristics.

1. Variable Renewable Energy, Transmission, and Diurnal Storage

One possible strategy for achieving the last 10% relies on existing technologies that are currently being deployed. This strategy builds more variable renewable energy, transmission, and diurnal (less than about 24-hour) storage. In this option, variable renewable energy and transmission capacity are sized to meet demand during daily stressful periods on the grid, with storage filling hourly supply gaps and curtailing excess variable renewable energy (learn more about curtailment in an NREL explainer video).

This strategy could be more cost competitive if there is greater long-distance transmission to move high-value variable renewable energy to demand centers, and if wind and solar technologies continue to improve. However, this approach could be more difficult if wind and solar land use and site constraints increase over time—another topic NREL has been studying, including the recent release of a new comprehensive data set of local ordinances for siting wind and solar energy projects.

2. Other Renewable Energy

Another possible strategy for the last 10% uses geothermal, hydropower, and biomass—technologies that could all play important roles in a zero-emissions power sector. These technologies do not rely on variable solar and wind resources and can potentially overcome the seasonal mismatch. However, resource availability, especially at locations with high electricity demand, might narrow their utilization to select regions only. These resources also have relatively high capital costs that might be economically challenging as a last 10% strategy.

Biomass-based generation could be another option to produce renewable electricity for the last 10%. This option has relatively low capital cost, but there are uncertainties and constraints on a steady and sustainable feedstock supply and the cost of biomass conversion.

3. Nuclear and Fossil with Carbon Capture

Nuclear and fossil fuel with carbon capture and storage (CCS) are widely cited as potentially important resources in a decarbonized electricity system because they are often reliably counted on throughout the year. Fossil CCS plants have not yet been deployed at scale, but some studies find significant deployment potential.

However, this strategy comes with challenges: limited recent deployment, cost uncertainties, and environmental and security considerations—and the high capital cost for low utilization could create economic barriers.

4. Seasonal Storage

Seasonal storage refers to using electricity to produce a storable fuel that can be used for generation over extended periods of time, even up to entire seasons of the year. Hydrogen or other hydrogen-derived fuels are currently the most promising options for seasonal storage. Converting hydrogen to electricity can be done using fuel cells or combustion technologies, which are being converted for hydrogen. These electricity generation options fueled by hydrogen could have low capital costs in the future and be viable as last 10% strategies. Key uncertainties with this strategy include the availability of the fuel (hydrogen) supply and delivery infrastructure.

5. Carbon Dioxide Removal

Carbon dioxide removal technologies can offset emissions from carbon-emitting power generation technologies by drawing down atmospheric carbon. This last 10% strategy is unique because it leverages other generation assets to support resource adequacy on the grid.

While there is unique value with carbon dioxide removal technologies, this last 10% option has deployment challenges. Very little carbon dioxide removal has been deployed yet worldwide, and future technology costs remain uncertain.

6. Demand-Side Resources

Demand-side resources, also called demand response or demand flexibility, are a unique last 10% solution compared to the other five strategies studied.

Demand-side resources reduce electricity consumption during times of system stress and help avoid investments in new peaking capacity. Through flexible scheduling or interruption of electricity consumption, they can also reduce operating costs or be used for important grid-reliability services. Capital costs for demand-side controls and communications equipment can be low, and direct operating costs are modest.

However, applying demand-side options as a last 10% strategy requires the resources to be reliably available over extended multiday periods. The scale of response needed on days of extreme events could exceed the demand-response potential, and flexibility from new electrified loads is uncertain.

"Given current technology costs and readiness, significant emissions reductions can occur through accelerated deployment of wind, solar, diurnal storage, transmission, and other renewable energy technologies," said Paul Denholm, NREL analyst and co-author of the study. "Other technologies could also play a big role if they become cost competitive and widely available. We will continue to study these possible solutions, but for now, the pathway to about 90% carbon-free electricity is increasingly clear. After all, getting to 100% requires first achieving 90%."

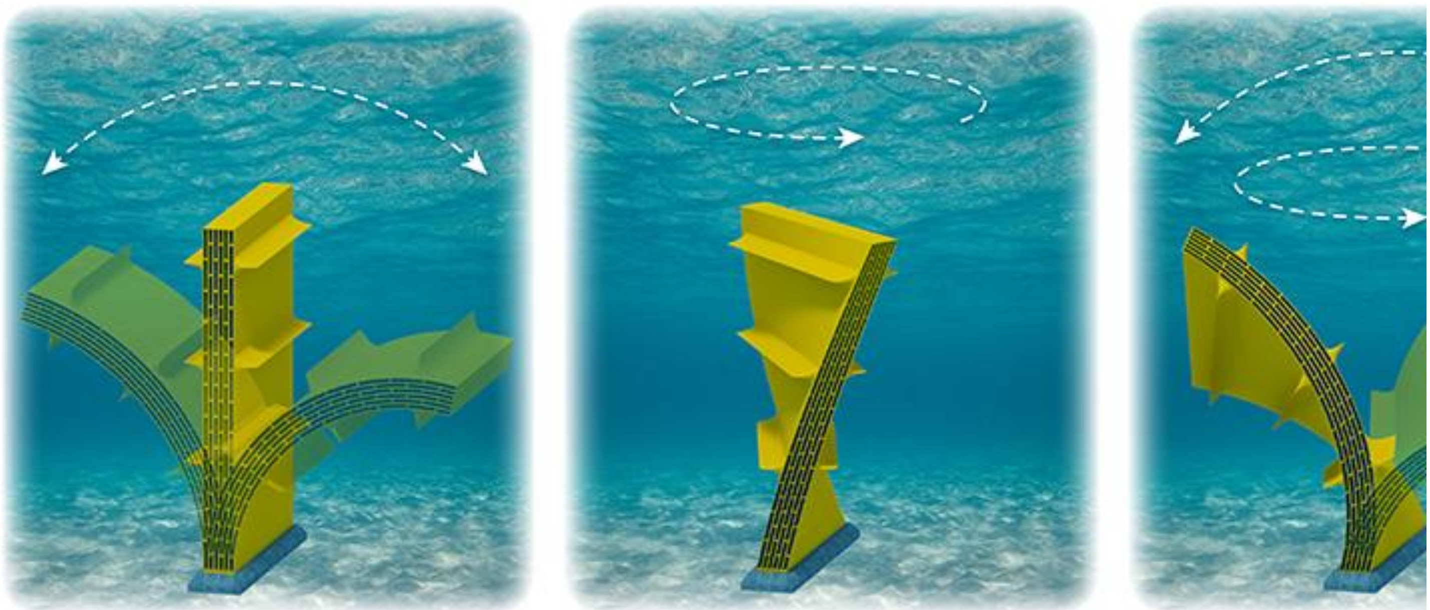
Chapter 2. Patented Wave Energy Technology Gets Its Sea Legs

New Technology Could Generate Electricity From Ocean Waves or Even Clothing, Cars, and Buildings

Sept. 19, 2022 | By Caitlin McDermott-Murphy

Imagine this: Clothing that charges your smart watch as you walk, buildings that vibrate in the wind and power your lights, a road that extracts energy from the friction created by moving cars, and flexible structures that change shape in ocean waves to generate clean electricity for communities around the world.

It is not science fiction. Someday, we could harness these naturally occurring energy sources thanks to a fledgling technology domain that just earned its first patent: distributed embedded energy converter technologies (or DEEC-Tec, pronounced deck-tech, for short).



A newly patented technology domain could build large, flexible structures from individual energy converters to create more cost-effective, highly efficient tools for generating clean energy from the ocean (and beyond). *Illustration by Besiki Kazaishvili, NREL*

The invention's first patent is specifically for applications in marine renewable energy—clean power generated from ocean and river waves, currents, and tides. But DEEC-Tec could eventually transform sources of everyday energy, including almost all physical motions or dynamic shape changes, into electricity or other forms of usable energy.

"The DEEC-Tec domain has legs and is growing," said Blake Boren, a senior engineer at the National Renewable Energy Laboratory (NREL) and the lead inventor on the patent along with Jochem Weber, chief engineer for NREL's water power program. DEEC-Tec might very well have the legs to move into buildings, clothing, and roads, but it is starting in the ocean. "The patent shows that we're gaining momentum in a fruitful area of research," Boren said.

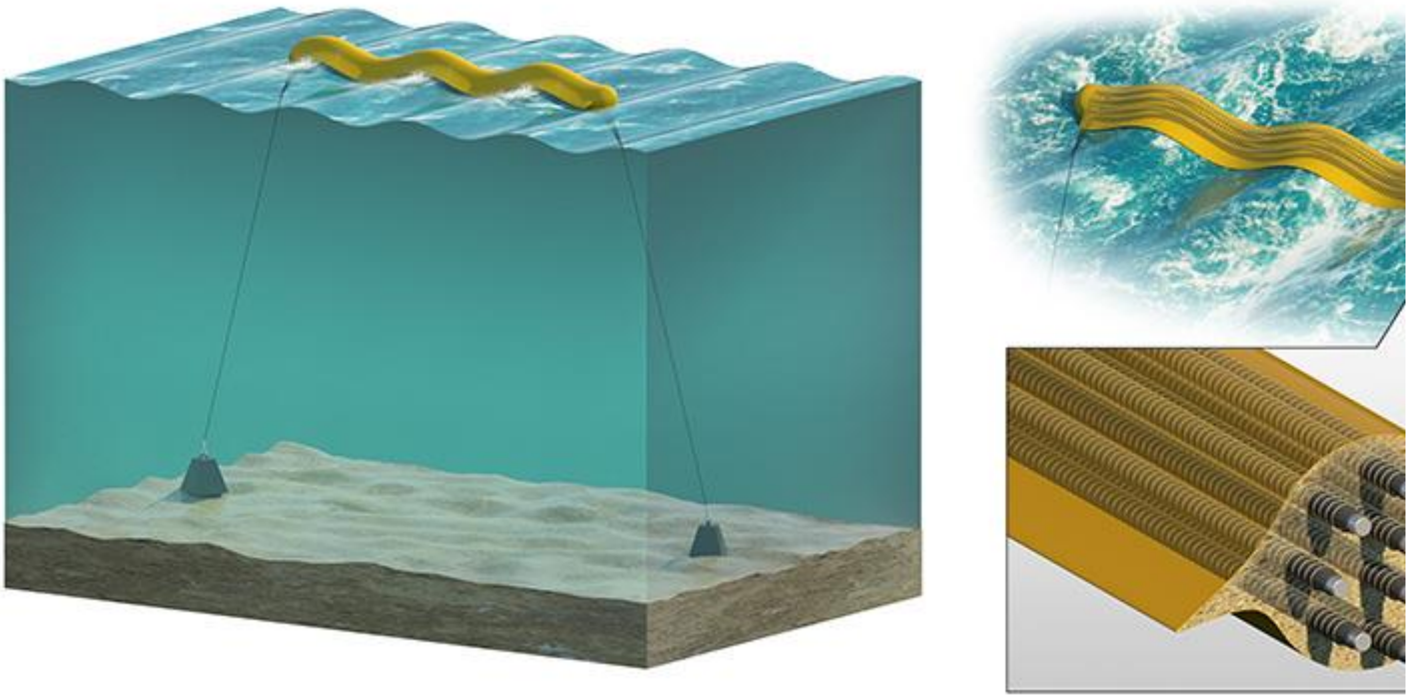
So, how does this promising DEEC-Tec domain actually work?

Picture a sea snake. That snake can swim thanks to an intricate partnership between its many pliable muscle cells. In the DEEC-Tec domain, individual energy converters work together, like muscle cells, to create a larger structure, much like the sea snake. Most devices use one generator to convert ocean energy into usable, clean, and renewable sources of energy, including electricity. But DEEC-Tec amasses its many tiny converters to form one larger, often flexible energy converter.

"DEEC-Tec gives researchers and developers an entirely new way of thinking about how to convert marine energy from ocean waves, tides, and currents into more usable forms of energy, such as electricity," Boren said.

Combined, these tiny energy converters can form the foundation of fabrics, bulkheads, support structures, and more, building a range of DEEC-Tec-based energy converting structures. For example, DEEC-Tec-based wave energy converters could look like balloons that contract and expand, snakes that undulate, or paddles that twist and bend to harness ocean wave energy.

These adaptable balloons, snakes, and paddles could come with big benefits, too. Flexible wave energy converters, also known as flexWECs, can harness and convert waves into usable energy throughout their entire structure. So, no matter where or how wave energy interacts with a device's structure, energy converters will be there to transform that wave into power.



Distributed embedded energy converter technologies (or DEEC-Tecs) can be built into numerous shapes, like snakes and balloons, to capture energy from a wide range of ocean environments. *Illustrations by Besiki Kazaishvili, NREL*

Because flexWECs do not concentrate ocean wave energy into a singular energy converter (like a lone rotary generator or hydraulic piston cylinder) or one power transmission system (like a drive shaft or gearbox), they avoid accumulating ocean wave forces that could potentially shut off or damage the machine. Indeed, other wave energy converters often use large steel frames to protect their rigid bodies from oceanic forces, but those frames can be expensive and heavy. Instead, flexWECs can go with the flow.

FlexWECs' frames could also enable them to harness energy from a far wider range of ocean locations and wave energy frequencies. "One day, there could be DEEC-Tec-based marine renewable energy farms off the coast of California, Oregon, or Washington, with these types of wave energy converters potentially powering coastal communities or the utility grid at large," Boren said.

High costs are one of the last major hurdles that the blossoming marine energy industry must overcome to start powering those communities. And DEEC-Tec's flexible archetypes could offer an especially cost-effective way to harness wave energy. Because flexWECs host far more than one energy converter, they could require fewer maintenance trips; if only a small group of tiny converters requires fixing, all others could continue operating.

FlexWECs can also be built with more sustainable, cost-effective materials, making them easier to install and control once out in the ocean. Greater control could mean increased energy production, allowing operators to adapt to changing ocean conditions to harness the greatest amount of potential energy.

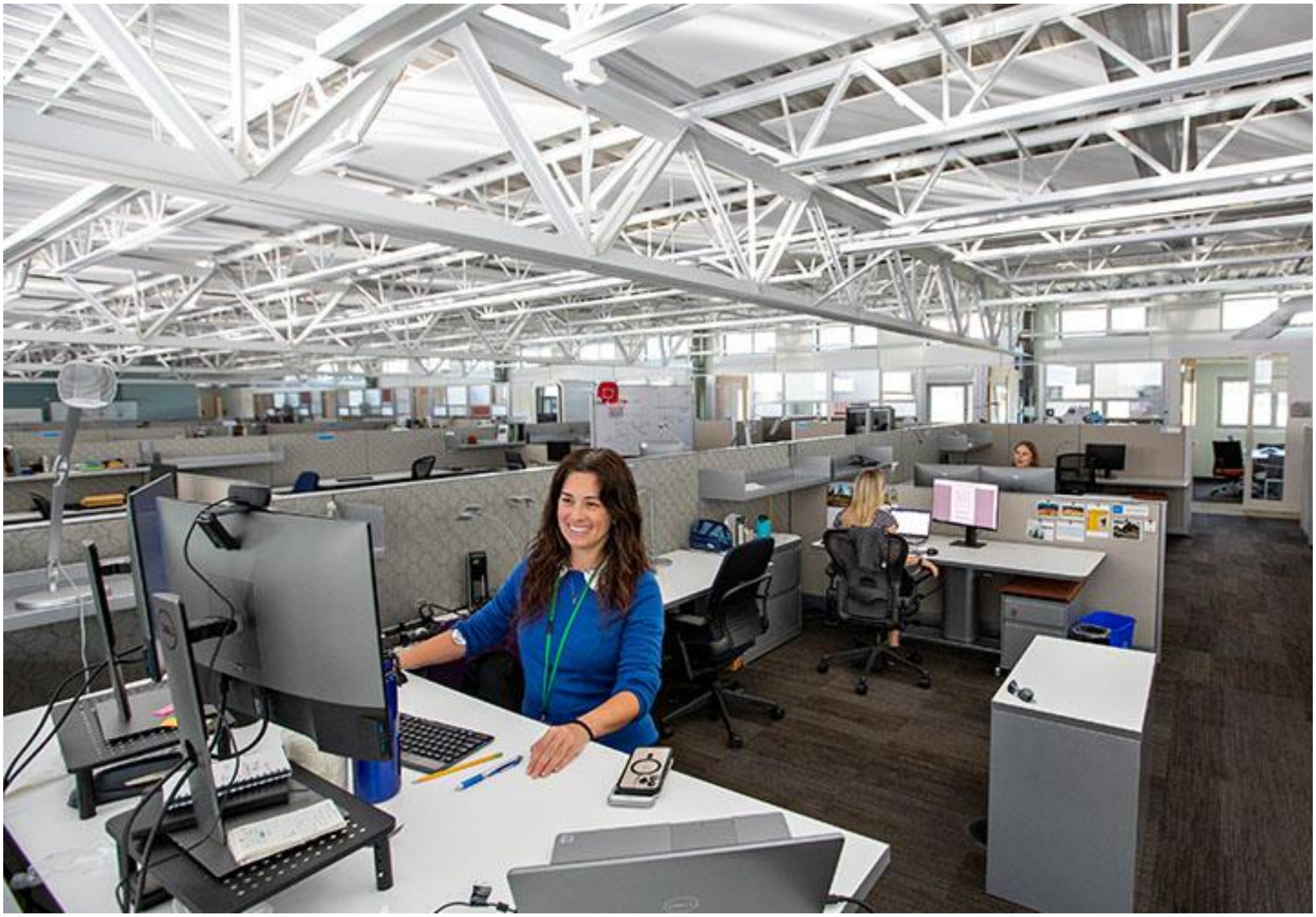
Because the DEEC-Tec domain is still relatively new, Boren and his team are working hard to explore exactly how these technologies could create a new generation of marine energy devices or other energy generating materials. And Boren's recent patent was a big push toward a DEEC-Tec future.

"The patent gives further credence as to what DEEC-Tec could become," Boren said. "Now, we have a patented foundation to further develop and promote DEEC-Tec both within NREL and with our external collaborators and industry."

Chapter 3. Considerations To Achieve a Sustainable U.S. Commercial Building Stock

New Study Led by the Joint Institute for Strategic Energy Analysis Identifies Drivers, Barriers, and Costs of Adopting Building Sensors and Controls Systems

Sept. 21, 2022 | By Madeline Geocaris



A building sensors and controls system, like one at the National Renewable Energy Laboratory's Research Support Facility, can make a building easier to operate, save energy, improve comfort for occupants, and more. *Photo by Werner Slocum, NREL*

Building sensors and controls systems are automated controls systems that can regulate a building's heating, ventilation, and air conditioning (HVAC), lighting, appliances, and more to increase energy efficiency. These systems can save building owners money, enable buildings to be grid-interactive, and support decarbonization.

Nearly 60% of U.S. commercial buildings over 50,000 square feet have sensors and controls systems, but only 13% of buildings under 50,000 square feet have the technology—meaning more than 75% of the U.S. commercial building stock has untapped efficiency potential.

The Joint Institute for Strategic Energy Analysis (JISEA) studied barriers and drivers of adopting building sensors and controls systems and created a full breakdown of costs. This work, which was done in partnership with the National Renewable Energy Laboratory (NREL), falls under JISEA's Clean Energy Manufacturing Analysis Center. The findings are published in a JISEA technical report.

"The technologies exist for the buildings sector to be more energy efficient and sustainable, but high market adoption is complicated," said Kim Trenbath, NREL researcher and lead author. "Our insights highlight the major considerations building owners take into account when deciding whether to adopt a sensors and controls system, so we can better understand what it will take to achieve widespread adoption."

Drivers and Barriers to Adoption

Based on interviews with building owners, contractors, controls vendors, analytics vendors, and researchers, JISEA finds that the biggest driver to adopting a building sensors and controls system is the operational benefits and insights. Building owners like that the technology allows them to automate building schedules, seasonal changes, and more, and that they don't have to call technicians as often. Building owners can also tap into operational insights such as energy consumption or occupancy patterns.

While the operational benefits garner interest among building owners, JISEA finds three key barriers to adopting a building sensors and controls system: (1) The systems can be confusing and/or complex, (2) owners do not have the skills or expertise to use the system, and (3) owners cannot justify the upfront cost.

"We find that the upfront cost and difficulty quantifying savings lead to a perception that these systems aren't profitable," said Ryan Meyer, NREL researcher and co-author. "But studies have shown widespread adoption could reduce energy costs by 29% across the commercial building sector."

To enhance system interoperability and usability, JISEA recommends consistency and standardization across controls technologies to support greater adoption, especially for buildings that historically have not implemented these technologies.

System Cost Breakdown

Knowing cost can be a barrier to adoption, JISEA created a complete cost breakdown for multiple building sensors and controls systems. Data came from several sources, such as project invoices and estimates and available cost information from various manufacturers.

Based on the data, JISEA finds 50%–75% of the cost of a building sensors and controls system comes from labor. Because the systems are complex, they require specialized labor. It is no longer sufficient for an installer to have the skills for even the most advanced HVAC systems because the new technology specifications require a more IT-focused skillset. The specialized labor results in higher costs. Labor rates and contractor pricing/markup vary regionally and can significantly impact overall cost. For example, a project that costs $780,000 in Dallas could cost upward of $1.8 million in New York City.

"There could be ways to allow equipment-embedded controllers to connect wirelessly and interoperate with the central control system, similar to how edge computing networks are operated, so there is less hardware, which would also reduce labor cost," Trenbath said. "These are the types of possible solutions that will be important to study moving forward to help remove barriers to adoption."

Chapter 4. Catalytic Process With Lignin Could Enable 100% Sustainable Aviation Fuel

NREL, MIT, Washington State University Collaboration Provides Pathway to Sustainable Jet Fuel

Sept. 22, 2022

Containers are of poplar biomass (left), the extracted lignin oil, and the resulting sustainable aviation fuel.

An underutilized natural resource could be just what the airline industry needs to curb carbon emissions.

Researchers at three institutions—the U.S. Department of Energy's National Renewable Energy Laboratory (NREL), the Massachusetts Institute of Technology (MIT), and Washington State University—report success in using lignin as a path toward a drop-in 100% sustainable aviation fuel. Lignin makes up the rigid parts of the cell walls of plants. Other parts of plants are used for biofuels, but lignin has been largely overlooked because of the difficulties in breaking it down chemically and converting it into useful products.

The newly published research demonstrated a process the researchers developed to remove the oxygen from lignin, such that the resulting hydrocarbons could be used as a jet fuel blendstock. The research, "Continuous Hydrodeoxygenation of Lignin to Jet-Range Aromatic Hydrocarbons," appears in the journal *Joule*.

Gregg Beckham, Ana Morais, and Earl Christensen are the researchers involved from NREL.

The paper points to the need to use sustainable sources for jet fuel as the airline industry has pledged to dramatically reduce carbon emissions. Airlines consumed 106 billion gallons of jet fuel globally during 2019, and that number is expected to more than double by 2050. Accomplishing the industry's goal of achieving net carbon neutrality during that same period will require a massive deployment of sustainable aviation fuel (SAF) with high blend limits with conventional fuel.

Jet fuel is a blended mixture of different hydrocarbon molecules, including aromatics and cycloalkanes. Current commercialized technologies do not produce those components to qualify for a 100% SAF. Instead, SAF blendstocks are combined with conventional hydrocarbon fuels. As the largest source of renewable aromatics in nature, lignin could hold the answer to achieving a complete bio-based jet fuel. This newly published work illustrates the ability of a lignin pathway to complement existing and other developing pathways. Specifically, the lignin pathway described in this new work allows the SAF to have fuel system compatibility at higher blend ratios.

Because of its recalcitrance, lignin is typically burned for heat and power or used only in low-value applications. Previous research has yielded lignin oils with high oxygen contents ranging from 27% to 34%, but to be used as a jet fuel that amount must be reduced to less than a half-percent.

Other processes have been tried to reduce the oxygen content, but the catalysts involved require expensive noble metals and proved to be low yielding. Researchers at the trio of institutions demonstrated an efficient method that used earth-abundant molybdenum carbide as the catalyst in a continuous process, achieving an oxygen content of about 1%.

The U.S. Department of Energy's Bioenergy Technologies Office and Center for Bioenergy Innovation funded the research.

Chapter 5. NREL Researchers Point to Path for Improved Wind Blade Recycling Rates

Aug. 30, 2022 | By Wayne Hicks

Photo by Werner Slocum, NREL

Researchers at the National Renewable Energy Laboratory (NREL) are considering circular economy strategies to mitigate the impact of wind turbine blades at the end of their useful lifespan.

The strategies are meant to address what to do with the blades once they are no longer needed, including using new materials that are easier to break down, extending their lifespan, and implementing various recycling options. Researchers at NREL have been investigating novel blade materials that are inherently more recyclable, thereby integrating solutions at the earliest stages of turbine component design.

“We want to see everything recycled, ideally,” said Aubryn Cooperman, an engineering analyst at NREL and coauthor of a new paper outlining the steps that need to be taken.

Realistically, however, as wind turbines reach the end of their useful, expected 20-year lifespan, some of the massive blades are bound to be discarded. More than 90% of wind energy facilities in the United States began generating power within the last decade. An estimated 10,000 to costs are a huge annually are expected to be at the end of their lifespan between 2025 and 2040.

Owners of wind power plants will be increasingly faced with decisions about what to do with these blades, the researchers noted in a new paper, “Regional Representation of Wind Stakeholders’ End-of-Life Behaviors and Their Impact on Wind Blade Circularity.”

In addition to Cooperman, the *iScience* article was coauthored by NREL researchers Julien Walzberg, Liam Watts, Annika Eberle, Alberta Carpenter, and Garvin Heath.

The scientists relied on a computer model that considers behavioral factors, which can undermine the viability of technical solutions. For example, a lack of trust in a new technology may keep it from reaching its full market potential. Therefore, the researchers point out, it is considered critical to understand the behavioral aspects of wind power industry stakeholders' decisions. Those stakeholders run the gamut from operators of wind sites to companies in the recycling business. The modeling tool, developed by researchers at NREL and publicly available, is the Circular Economy Wind Agent-Based Model.

The researchers said that in the absence of policy change or recycling technology development, as much as 78% of decommissioned blades are expected to end up in landfills, though that still would be a relatively small percentage of the amount of discarded waste at an estimated 1% nationwide in 2050. Among the factors hindering recycling are high transportation costs and subjective norms, which discourage people from recycling the blades if they see others not already doing so. By encouraging enough early adopters, recycling blades would become the norm.

"Transportation costs are a huge factor, because the blades themselves are huge," said Walzberg, the paper's lead author. "If your recycling facility is far away, that's going to make it a barrier for you to try to recycle."

Lowering those transportation costs could make a significant difference in how the old blades are disposed of. The blades are typically made of steel, plastic, and composite materials. While many of the materials now commonly used for the blades are easily broken down, they can be shredded with the right equipment.

"Shredding the blades makes them smaller and easier to ship to a recycling facility," Walzberg said. "That's kind of a low-hanging fruit. But you need to be able to shred the blades before transportation."

Even reducing the cost of shredding blades by a third before transportation could decrease the cumulative landfill rate below 50%, the scientists calculated in the new study. Another scenario that involves boosting early adoption of recycling so that it becomes the norm could bring the figure below 10%.

Walzberg said regulations could help boost recycling numbers as well and pointed to laws enacted to keep lead-acid batteries from landfills and old rubber tires from being burned.

The researchers said future work could study how increasing the number of recycling facilities for wind turbine blades could change the results. Meanwhile, other NREL scientists are already working on using new materials for blades that are intended to improve their recyclability.

The journal article builds on research published last year by Cooperman, working alongside Eberle and another NREL colleague, Eric Lantz. That article revealed “more profound shifts in recycling technologies, blade materials, or policy may be needed to move towards a circular economy for wind turbine blades.”

Funding for the research came from the U.S. Department of Energy’s Advanced Manufacturing Office and the Office of Strategic Programs.

Chapter 6. Growing Plants, Power, and Partnerships Through Agrivoltaics

Solar and Agriculture Pair Well Together, Thanks to Planning and Cooperation

Aug. 18, 2022 | By Harrison Dreves

Solar arrays can make a great home for grazing livestock, with the panels offering shade and shelter to the animals, who in turn keep the vegetation under the panels trimmed. *Photo from Lexie Hain, Lightsource bp*

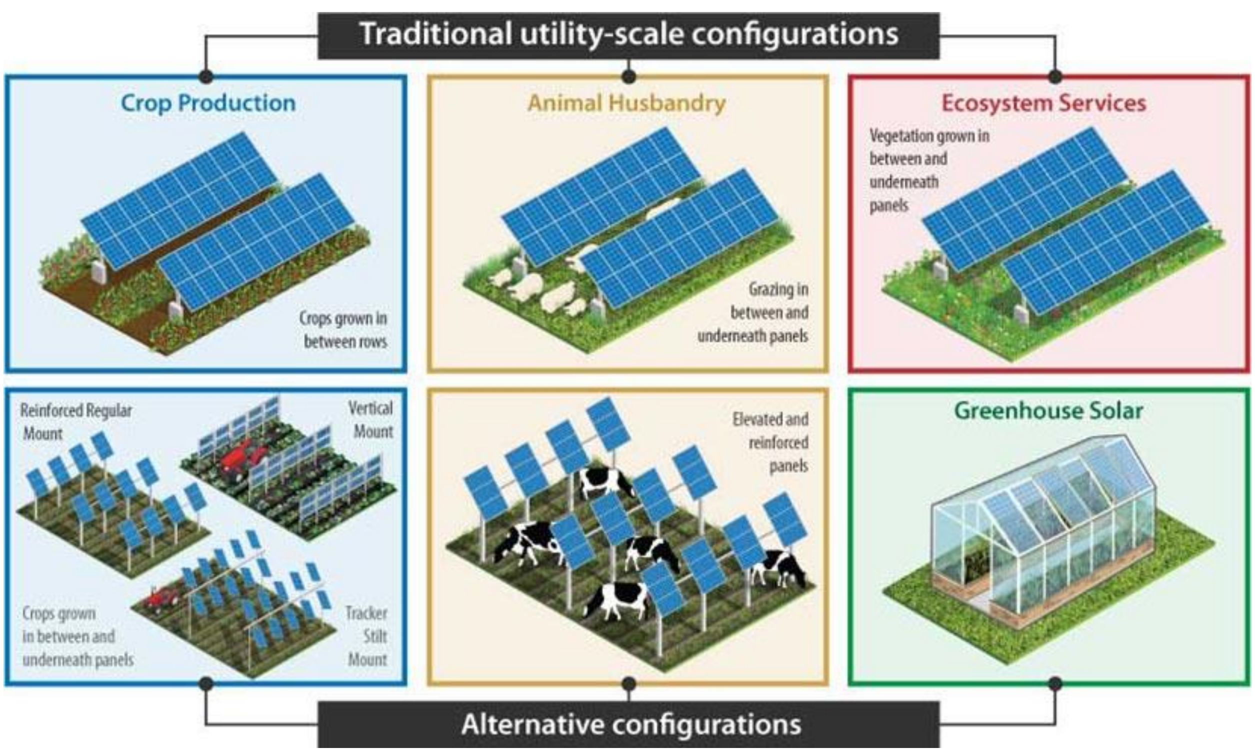
It is hard to find a flock of sheep nestled under an array of solar panels.

"Sheep are late risers. You won't hear them when you enter the site for an early morning walk. What you hear first are insects: crickets, little frogs. It feels alive to you," said Lexie Hain, a farmer in the Finger Lakes region of New York and director of agrivoltaics for Lightsource bp. "The flock loves to lie under the panels, so finding them often involves an element of surprise."

Hain grazes sheep underneath solar photovoltaic (PV) installations. Her flocks keep the plants under the rows of PV panels trimmed, saving the installation's owner the cost of mowing. And Hain's sheep get to eat for free (and may even be paid for it).

This concept—of using PV installations to both create renewable energy and provide space for local agriculture or native habitats—is known as "agrivoltaics."

Both solar developers and those in the local community who care for the land—whether as farmland, rangeland, or native habitats—can benefit from agrivoltaics. And when all sides understand how they can benefit each other, low-impact solar development becomes easier.



Agrivoltaics includes many different uses. Agrivoltaics systems can be installed in the same basic row layout as a traditional large-scale solar plant—or they can be modified to provide extra space for light, animals, or farm equipment to move under and between them.

Letting Solar and Agriculture Work for Each Other

These are among the most important findings of an ongoing agrivoltaics research project called Innovative Solar Practices Integrated with Rural Economies and Ecosystems (InSPIRE).

Led by the National Renewable Energy Laboratory (NREL) and funded by the U.S. Department of Energy's Solar Energy Technologies Office, InSPIRE has just completed its second, three-year phase of research into the synergies between solar energy and agriculture.

In its first phase, InSPIRE tried to quantify the benefits of agrivoltaics and record some early best practices in the emerging field. The project adopts a big-tent approach to agrivoltaics, welcoming any dual use of solar-occupied land that provides ecological or agricultural benefits. That could mean grazing cattle or sheep, growing crops, cultivating pollinator-friendly native plants, or providing ecosystem services and restoring degraded soil.

Beneath Solar Panels, the Seeds of Opportunity Sprout

For InSPIRE's second phase, NREL and dozens of partnering organizations carried out agrivoltaics field research across the nation to study what makes an agrivoltaics project successful.

"Through our work, which spans multiple regions, configurations, and agricultural activities, we've seen so many initial promising results," said Jordan Macknick, NREL's lead energy-water-land analyst and principal investigator for the InSPIRE project. "Now, our challenge is to figure out how to scale up and replicate these successes."

NREL Director Martin Keller tastes the difference between the control group lettuce and experimental lettuce grown in the agrivoltaic facility at Jack's Solar Garden. Photo by Joe DelNero, NREL

Across the many different types of solar and agricultural sites that participated in InSPIRE's second round, a key lesson emerged: Partnerships matter. Agrivoltaics is not necessarily more expensive than traditional solar development, but it can be more complex.

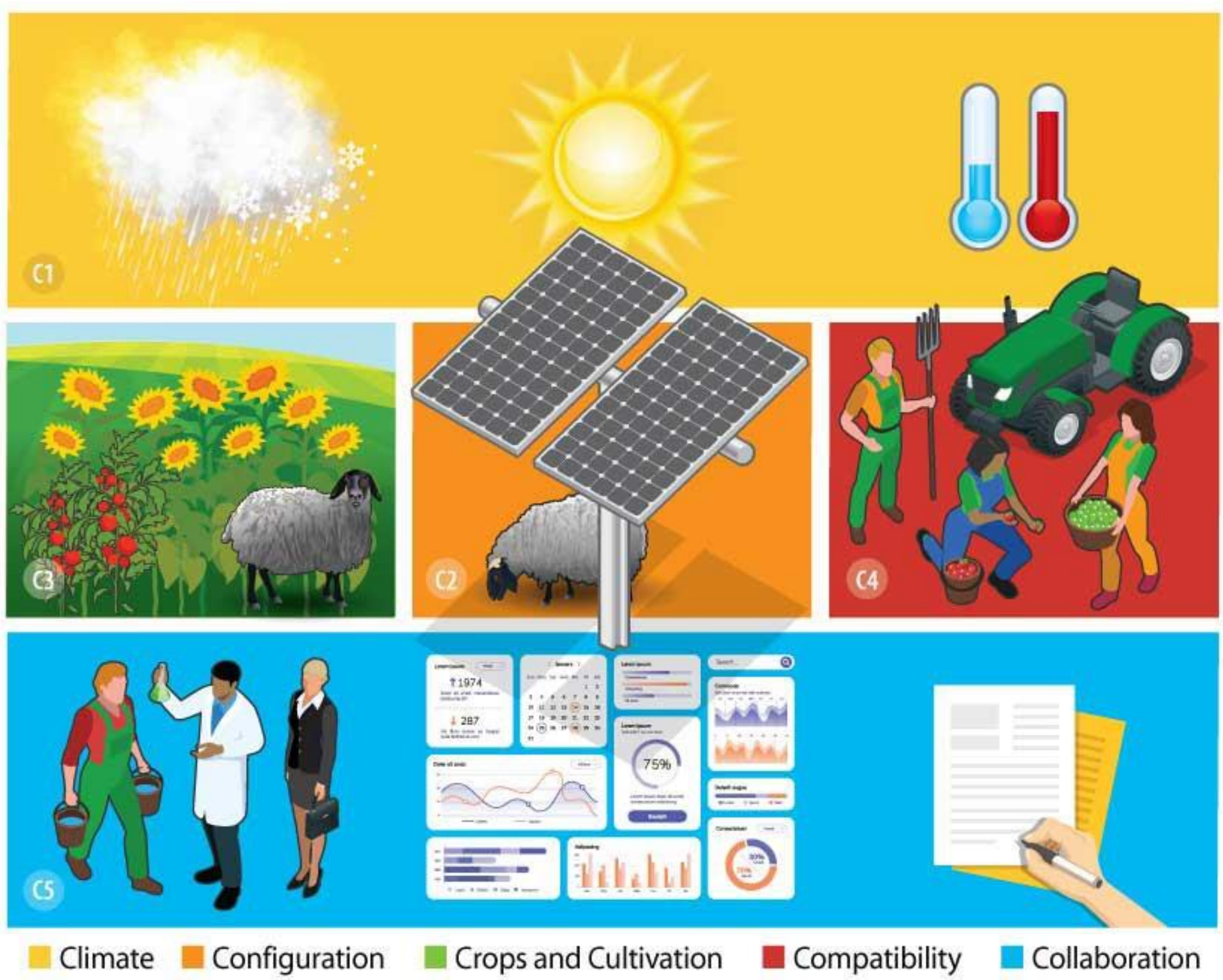
A successful agrivoltaics project requires two or more groups who often have very different priorities—the farmer or land manager and the solar developer—to find a solution that works for both. Local community acceptance is also important.

"Solar projects are commonly built on agricultural lands, which then creates the challenge of balancing food security with increasing renewable energy production," said Brittany Staie, an NREL research intern studying decarbonization of the agricultural sector. "Agrivoltaics gives us the opportunity to explore growing food while also producing clean electricity on the same piece of land."

What Matters: "The Five C's" of Agrivoltaics

The InSPIRE project found five central elements that lead to agrivoltaics success, summarized as "the five C's":

- **Climate**, Soil, and Environmental Conditions — The ambient conditions of a location must be appropriate for both solar generation and the desired crops or ground cover.
- **Configurations**, Solar Technologies, and Designs — The choice of solar technology, the site layout, and other infrastructure can affect everything from how much light reaches the solar panels to whether a tractor, if needed, can drive under the panels. "This infrastructure will be in the ground for the next 25 years, so you need to get it right for your planned use. It will determine whether the project succeeds," said James McCall, an NREL researcher working on InSPIRE.
- **Crop Selection** and Cultivation Methods, Seed and Vegetation Designs, and Management Approaches— Agrivoltaic projects should select crops or ground covers that will thrive under panels in their local climate and that are profitable in local markets.
- **Compatibility** and Flexibility — Agrivoltaics should be designed to accommodate the competing needs of solar owners, solar operators, and farmers or landowners to allow for efficient agricultural activities.
- **Collaboration** and Partnerships — For any project to succeed, communication and understanding between groups is crucial.



A recently published NREL report breaks out each of the "five C's" in detail, reflecting the many lessons learned during the last three years of InSPIRE research.

But, as a major research institution, NREL did not focus only on lessons for solar developers, farmers, and landowners. InSPIRE also captured lessons for agrivoltaics researchers. Just as solar developers and landowners need to communicate and understand each other's goals and concerns, agrivoltaics researchers must also coexist under the panels. The latest InSPIRE report is full of suggestions for how to make that happen.

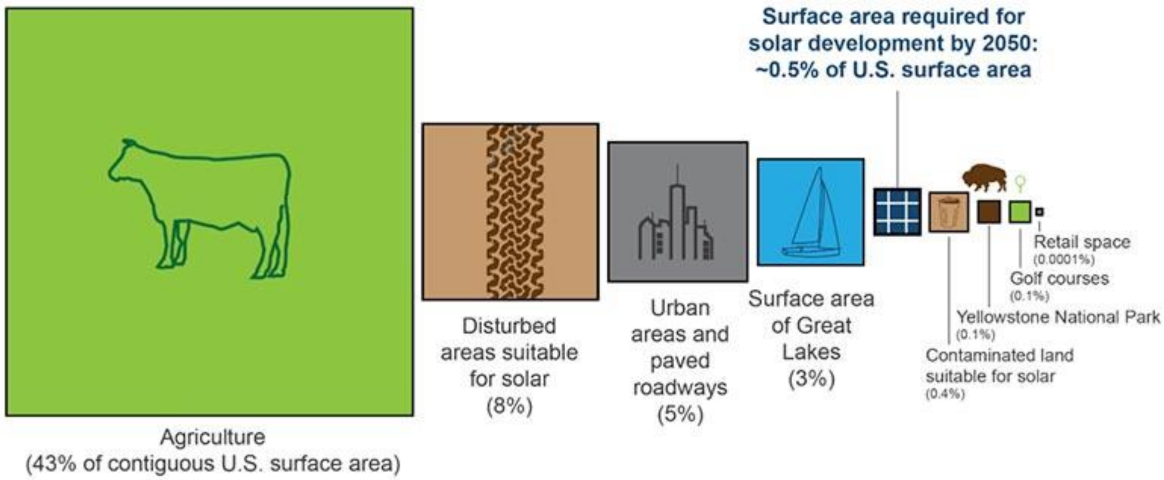
What about the local impacts of solar on water runoff?

A companion project to InSPIRE, Photovoltaic Stormwater Management Research and Testing (PV-SMaRT), looks at the impacts that solar installations can have on how water collects on and moves through the landscape. Currently, many local regulations treat solar installations similar to parking lots with respect to water runoff, requiring the solar projects to install large drainage basins and other infrastructure to capture water runoff from rainstorms. However, the soil and vegetation underneath these panels can absorb much more water than a paved surface and can play an important role in reducing erosion.

NREL's PV-SMaRT project is conducting field research at five sites across the country to measure how water runoff occurs at solar installations, including how construction techniques and vegetation can impact water runoff. This research could help local and state governments set new regulations that require smaller drainage basins for future solar installations, reducing the cost of solar energy.

Building an American Agrivoltaics Industry

From the start, InSPIRE has acted as a home for the American agrivoltaics community. Now, that community is expanding. PV installations are expected to require between 4 and 10 million acres of land by 2050, with flat, sunny farmland making up some of those acres.



The NREL-authored Solar Futures Study models a future in which solar energy supplies 45% of U.S. electricity in 2050, with other zero-carbon sources providing the rest. The land area necessary to host that solar energy, while smaller than many other land uses, is significant. This calculation of land area does not account for any siting of solar on rooftops, bodies of water, or in agrivoltaics configurations.

"One thing InSPIRE has done really well is to create a community of people who are thinking differently about PV solar design and management. Universally, following an InSPIRE conference call hearing scientists and industry practitioners share their results, there's tremendous energy and optimism for the challenge and opportunity ahead of us," said Rob Davis of Connexus Energy, the Midwest's largest electric co-op. Davis is a member of InSPIRE's multisector community advisory group, Agriculture and Solar Together: Research Opportunities (ASTRO), which also recently released a report summarizing its impact.

InSPIRE already represents the largest, longest-running, and most comprehensive agrivoltaics research effort in the world, having supported agrivoltaics site design or ongoing research at 28 sites in 11 U.S. states, Puerto Rico, and the District of Columbia. Some of these sites involve direct research, some involve research design and consideration, and some involve ongoing consultation and mentoring of partners.

For its third round of research from 2022–2024, InSPIRE is focusing on expanding the agrivoltaics research community and creating foundational resources to support the community nationally and internationally. These efforts include partnering with the AgriSolar Clearinghouse to support landowners and farmers interested in adopting agrivoltaics.

"As research interest in agrivoltaics grows, the InSPIRE project is transitioning from being the main source of research to enabling all the others who are doing agrivoltaics research," Macknick said.

In 2022, InSPIRE began tracking all agrivoltaics projects across the United States. The project will also host workshops for the research community and will develop agrivoltaics research protocols and a road map for future research. InSPIRE will also be adding more research sites in more places—for example, on tribal lands in partnership with Indigenous communities.

NREL Brings Agrivoltaics Home

In June 2022, InSPIRE added its 29th research site. Working with other solar research colleagues (and staff volunteers) at NREL, the InSPIRE team planted a half-acre garden under a set of solar panels on NREL's main campus in Golden, Colorado. The site will study how plants like tomatoes, peppers, kale, and native grasses and flowers grow underneath panels in Colorado's arid Front Range region.

The solar panels overhead are part of a different NREL experiment, which studies how changes in the ground surface can reflect more or less light onto two-sided (or "bifacial") solar panels that absorb light bounced up from the ground. In this two-for-one project, InSPIRE gains a new test site, while NREL's PV field performance team is able gather data on how crops reflect light back onto solar panels.

"Bifacial technology represented at least half of utility-scale installations in 2021," said Silvana Ovaitt, an NREL PV reliability researcher. "Pairing these panels up with crops to study the interactions between plants—creating a microclimate and modifying the ground albedo—and bifacial modules on trackers—creating shading for the plants through their tracking—is of great relevance for the PV community seeking to maximize agricultural and solar performance."

But the new site on the NREL campus means even more than that.

"I'm excited to have an agrivoltaics site right here on our home campus," Macknick said. "We get to involve the whole NREL community and their capabilities, which will advance the state of the science. And we'll be able to serve the produce we grow in the community, so everyone can actually taste the fruits of our science."

Chapter 7. Assessing Power System Reliability in a Changing Grid, Environment

NREL's Energy Analysts Use the "Three Rs" Concept To Provide a Fuller Picture of Power System Reliability With Changing Resource Mixes, Grid Conditions

Aug. 10, 2022

How the grid is planned is changing due to many factors, including increasing effects from climate change, like wildfires. *Photo from iStock*

From increasing decarbonization, electrification, and distributed generation, to more frequent extreme weather events from climate change, the electric power system is undergoing immense change. These factors impact how the grid is planned and operated to maintain safe and reliable power.

The North American Electric Reliability Corporation—which is dedicated to monitoring the overall health of the bulk power system and minimizing reliability and security risks—published the 2022 Summer Reliability Assessment. The report identified several areas that are at higher risk this summer due to extreme drought conditions, transmission lines out of service, higher demand, and more. Heightened reliability risks make power system planning even more important.

To frame the issue of reliability, researchers at the National Renewable Energy Laboratory (NREL) use the "three Rs of power system reliability": resource adequacy, operational reliability, and resilience. All three Rs are required for a safe and reliable power system. This concept has guided recent NREL studies on maintaining reliability with a changing grid and environment.

There is no single absolute definition for each of the three Rs, and some aspects overlap. In addition, the metrics used to measure power system reliability are still being developed and are currently an important conversation within the grid planning space. However, the three Rs can inform holistic power system planning and operation to ensure a safe and reliable grid.

"Every region is different and requires its own unique analysis, but the three Rs can help to provide a more comprehensive picture of power system reliability and risk to grid planners, regulators, and policymakers," said Paul Denholm, principal energy analyst at NREL. "The three Rs can also guide the evolution of power system reliability metrics moving forward."

Resource Adequacy: Sufficient Spare Capacity

Resource adequacy is the ability of the power system to supply enough electricity—at the right locations—to keep the lights on, even during extreme weather days or times when load drops. Resource adequacy is typically measured by the probability of an outage over an extended amount of time. When evaluating resource adequacy, NREL broadly considers uncertainty in both supply and demand.

Load uncertainty includes increasing electric demand, stressful load periods, and more. Supply uncertainty includes the occasional but expected common outages in power plants, transmission and distribution lines, and other grid equipment. Supply uncertainty also includes the availability of variable resources like solar and wind, as well as energy storage and demand response, particularly during times of system stress.

An adequate system has enough available resources (e.g., spare capacity and/or flexible load) to replace capacity that fails, is out of service for maintenance, or is unavailable due to fuel constraints. The transmission system is also important to ensuring resource adequacy because it delivers generation from many resources to load sites and enables access to a greater diversity of variable renewable resources and load across neighboring regions.

With more renewables being added to the grid, resource adequacy must increasingly account for the variability of renewable energy supply, role of storage, changes in demand patterns, and impact of transmission outages and interregional coordination.

Operational Reliability: Ability To Respond in Real Time

Operational reliability is the ability of the power system to balance supply and demand in real time by managing variability, ramping constraints, and flexible loads—including immediately following an "event" like a large power plant or transmission line failure. A reliable power system can keep the lights on during these unexpected events with power plants that can rapidly vary output or end users that can reduce their electricity consumption.

One aspect of operational reliability is operating reserves, or available spare capacity that actively responds during an event to help balance power and maintain stable frequency. For example, inertia on the grid allows time for the mechanical systems that control most power plants to detect and respond to a failure.

Grid services like inertia have traditionally been provided by conventional fossil, nuclear, or hydroelectric plants that use spinning synchronous generators. However, wind, solar photovoltaics, and batteries are inverter-based resources, meaning they rely on power electronics, or inverters, to generate grid-compatible electricity.

"As more conventional generators are replaced with inverter-based resources, it's important to understand how they can maintain a safe and stable grid," said Mohit Joshi, NREL grid analyst who supports developing countries in South Asia and Southeast Asia with their long-term power system planning.

Resilience: Ability To Bounce Back

Resilience is not as clearly defined as resource adequacy or operational reliability. The Federal Energy Regulatory Commission defines it as "the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event."

Parts of resilience overlap with resource adequacy and operational reliability, but generally it captures how well a system recovers or how quickly power can be restored after an outage. Resilience also includes more extreme events than the typical outages considered with resource adequacy and operational reliability.

"Over the years with increasing renewable generation, electric vehicles, demand response, and other emerging technologies, we have learned that there doesn't have to be a tradeoff between decarbonization and power system reliability," Joshi said. "About a decade ago, there was skepticism in South Asian and Southeast Asian countries whether the power system could operate with wind and solar, but in some grids, we have seen instantaneous contributions of variable generation up to 100%. Moving forward, there will be new technologies and there may be new challenges, but through our research we can find solutions to continue to ensure a low-carbon, safe, and reliable grid."

Chapter 8. Increased Spacing of Solar Panels Comes With Benefits

Oct. 24, 2022 | By Wayne Hicks

Researchers have determined that moving solar arrays farther apart from each other can have benefits both in economics and efficiency. *Werner Slocum, NREL*

Moving rows of solar panels farther apart can increase efficiency and improve economics in certain instances by allowing greater airflow to whisk away some heat, according to a new analysis.

Solar panels work by capturing sunlight and converting that to electricity, but the accompanying heat can decrease their power output slightly. The analysis looked beyond current operating assumptions that considered only the amount of sunlight, wind speed, and ambient temperature.

“But in reality, when you look at the layout of the system, like how the modules are spaced apart, what angle they're at, how high they're off the ground—that all affects airflow,” said Matthew Prilliman, a researcher at the National Renewable Energy Laboratory (NREL) whose expertise includes modeling the performance of photovoltaic (PV) systems.

Prilliman is lead author of the paper “Technoeconomic Analysis of Changing PV Array Convective Cooling Through Changing Array Spacing,” which appears in the *IEEE Journal of Photovoltaics*. Other co-authors from NREL are Janine Keith and Tim Silverman. Outside NREL, the co-authors are Sarah Smith and Raúl Bayoán Cal from Portland State University and Marc Calaf and Brooke Stanislawski from the University of Utah, Salt Lake City. (Stanislawski is now with NREL.)

The temperature of a PV module is second only to the amount of sunlight it receives in terms of impact on module electrical output. The maximum power output of a module drops by 0.3% to 0.5% per degree increase in module temperature. Sunlight is the primary driver of the module temperature, with the wind speed having a secondary effect.

The analysis, which relied on NREL’s System Advisor Model, demonstrated that a greater separation between rows would improve the performance of a PV system by allowing airflow to cool down the solar modules. Prilliman said few previously used computer models considered the changes in heat transfer caused by differences in how an array is configured.

“This is relatively unexplored territory,” he said.

The research could be particularly relevant for the growing field of agrivoltaics, in which crops are planted adjacent to or below solar panels. The changing land usage for different layouts would affect the placement of crops, which could in turn also affect wind flow.

“Increasing spacing could enable more varieties of crops and more types of agricultural equipment to be utilized in agrivoltaic systems,” said Jordan Macknick, who leads a different NREL research project focused on agrivoltaics. “That could potentially make these spaced-out solar systems more cost-effective and compatible with larger-scale agriculture."

By distancing the panels further, the amount of ground-reflected irradiance on a solar module increases and the incidence of modules casting shade on each other decreases. The increased spacing also allows greater wind flow, which can result in lower module temperatures and higher energy output.

The researchers did not specify how far apart the panels should be because each PV system is different and depends upon local conditions. They did point out the greatest improvements came in climates with low average annual ambient temperatures and moderate to high average annual wind speeds.

A greater separation of rows carries additional costs, the researchers found. Notably, more land is needed as the arrays are spaced out more. In addition, wiring costs increase as the arrays are more spread out. Crucially, the researchers determined the benefits outweigh the costs in many cases.

Chapter 9. BOTTLE Project Outlines New Strategy for Valorization of Mixed Plastic Waste

Oct. 13, 2022

Combining chemical and biological processes is a promising new strategy for the valorization of mixed plastic waste, according to researchers with the Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment (BOTTLE) Consortium.

Waste plastics have emerged as a global energy and pollution problem as ineffectively managed materials continue to accumulate in landfills and the environment. Only about 5% is recycled in the United States, with existing strategies requiring separated and clean plastic inputs to operate effectively.

Different plastics comprise different polymers, each with their own unique chemical building blocks. When polymer chemistries are mixed—either in a collection bin or formulated together in materials such as multilayer packaging—recycling becomes expensive and difficult because each polymer often must be separated prior to chemical deconstruction. The BOTTLE researchers developed a process that can convert mixed plastics to a single chemical product, working toward a solution that would allow recyclers to skip sorting plastic by type.

“This is a potential entry point into processing plastics that cannot be recycled at all today,” said Gregg Beckham, a senior research fellow at the U.S. Department of Energy’s National Renewable Energy Laboratory (NREL) and head of BOTTLE. Beckham is the senior author of a new paper published in the journal *Science* that details work creating a tandem chemical and biological process to produce single high-value products from waste plastic. The paper, “Mixed plastics waste valorization through tandem chemical oxidation and biological funneling,” was co-authored by NREL researchers and BOTTLE team members from the Massachusetts Institute of Technology, Oak Ridge National Laboratory, and the University of Wisconsin–Madison.

The process builds upon work pioneered a decade ago: Chemical oxidation can be used to break down a variety of plastic types, which was developed by a scientist from DuPont. The NREL researchers built on this chemistry, which uses oxygen and catalysts to break down the large polymer molecules into their smaller chemical building blocks.

“The chemical catalysis process we have used is just a way of accelerating that process that occurs naturally, so instead of degrading over several hundred years, you can break down these plastics in hours or minutes,” said Kevin Sullivan, a postdoctoral researcher at NREL and co-author of the paper.

They applied the process to a mixture of three common plastics: polystyrene (PS), used in disposable coffee cups; polyethylene terephthalate (PET), used in single-use beverage bottles, polyester clothing, and carpets; and high-density polyethylene (HDPE), used in many common consumer plastics, often associated with milk jugs. Although not part of the initial proof-of-concept work, the team noted that this method could be extended to include other plastics including polypropylene (PP) and polyvinyl chloride (PVC). This will be a focus of ongoing efforts for the group.

This oxidation process breaks down the PS, PET, and HDPE plastics into a complex mixture of chemical compounds—including benzoic acid, terephthalic acid, and dicarboxylic acids—that would require advanced and costly separations to yield pure products. For the BOTTLE researchers, that is where biology came into play.

The BOTTLE team engineered a robust soil microbe, *Pseudomonas putida*, to biologically “funnel” the mixture of intermediates to single products: either polyhydroxyalkanoates (PHAs), which are an emerging form of biodegradable bioplastics; or beta-ketoadipate, which can be used to make new performance-advantaged nylon materials.

“Biological funneling simply means we’ve engineered the metabolic network of a microbes to direct the carbon from a large number of substrates to a single product,” said Allison Werner, a co-author on the study. “To do this, we take DNA from nature—usually other microbes—and paste it into *Pseudomonas putida*'s genome. The DNA is transcribed into RNA, which in turn is translated into proteins that perform diverse biochemical transformations, forming a new metabolic network and ultimately enabling us to capture more carbon and to tune where it goes.”

The researchers have previously used *Pseudomonas putida* to valorize chemical mixtures from lignin—the hardy parts of cell walls in plants that are difficult to break down. After considerable success in that space, the researchers decided to turn it loose on the plastics problem.

“Moving from lignin to plastics, there were similarities but also new challenges,” said Kelsey Ramirez, a technician at NREL and co-author on the project. “We were able to adapt some of the analytical methods, but we know there is a lot of work to do to understand and quantify all the additives, dyes, and other unknowns present in postconsumer plastics today.”

The authors emphasize that the engineered bacteria do not degrade plastics directly but rather upcycle the deconstructed mixture of chemical oxygenates into a single product. “If you took the bacteria that we use right now, and you combine it with polyethylene, the bacteria will die, and the plastic will stay there,” Beckham said. The oxidation process, he said, converts the recalcitrant plastic polymers into small molecules the bacteria can be engineered to consume. “After some engineering, these compounds are excellent carbon and energy sources for microbes.” Genetic and metabolic engineering enabled the team to tune where the microbe funnels that carbon, in this case to PHAs or to beta-ketoadipate materials that can be used for new performance-advantaged plastics.

An NREL mission to the International Space Station will test whether microgravity improves the bacterial upcycling process.

The other co-authors from NREL are Lucas Ellis, Jeremy Bussard, Brenna Black, David Brandner, Felicia Bratti, Bonnie Buss, Xueming Dong, Stefan Haugen, Morgan Ingraham, Mikhail Konev, Joel Miscall, Isabel Pardo, and Sean Woodworth.

Chapter 10. Integrating Carbon-Free Generation in the Carolinas

NREL and Duke Energy Investigate the Pathways to a Decarbonized Grid

Oct. 5, 2022

NREL partnered with Duke Energy to analyze future scenarios of renewable energy integration. *Photo from iStock*

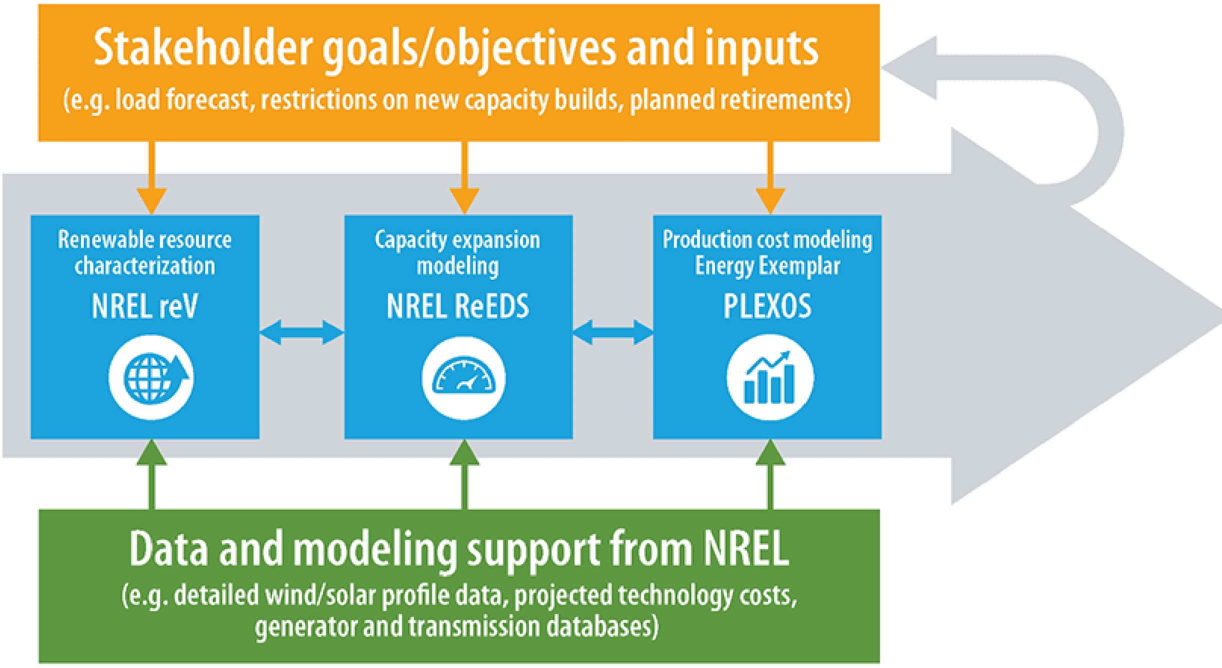
Like many utilities, Duke Energy is looking for opportunities to reduce carbon emissions in coordination with policymakers and regulators. In 2021, North Carolina passed legislation codifying a 70% emissions-reduction target for 2030 and a net-zero carbon dioxide emissions target for 2050, with Duke Energy also establishing its own goal of a net-zero CO_2 emissions power system by 2050.

Achieving these targets while providing reliable and affordable power in the Carolinas is a central focus for Duke Energy's long-term planning. To support this transition, the National Renewable Energy Laboratory (NREL) has engaged in a multiyear project with Duke Energy that identified least-cost pathways for carbon-free power in the region. Although specific to Duke Energy's system, this Carbon-Free Resource Integration Study offers a modeling approach that can be customized for any utilities' carbon-free resource planning, using a variety of accessible NREL tools.

Planning Tools for Renewable Power Systems

NREL's project with Duke Energy included two phases. In Phase 1, the researchers conducted a preliminary analysis of adding substantial new solar energy to the system, in which they ratcheted solar output up to 30% of annual generation—leading to an 80% carbon-free system when considering output from wind, nuclear, and hydro—showing how solar curtailment ramps up as more is added to the system in future deployment scenarios. Read the full Phase 1 report to learn more.

The recently completed Phase 2 analysis provided a deeper analysis into the potential investments, costs, and effects on operations as Duke Energy integrates carbon-free energy. In this phase, NREL deployed a suite of planning tools to evaluate scenarios representing Duke Energy in both the near term (2030) and long term (2050). NREL released its Phase 2 report this week, which is the subject of the rest of this news article.



Flowchart illustrates methods and modeling tools used in the NREL Carbon-Free Resource Integration Study.

The NREL researchers began with high-resolution maps of the Carolinas' wind and solar resource. This resource assessment includes hourly resource profiles and removes areas that would not be suitable for development. By plugging these maps into NREL's open-source Renewable Energy Potential model, the researchers identified developable wind and solar sites in the Carolinas.

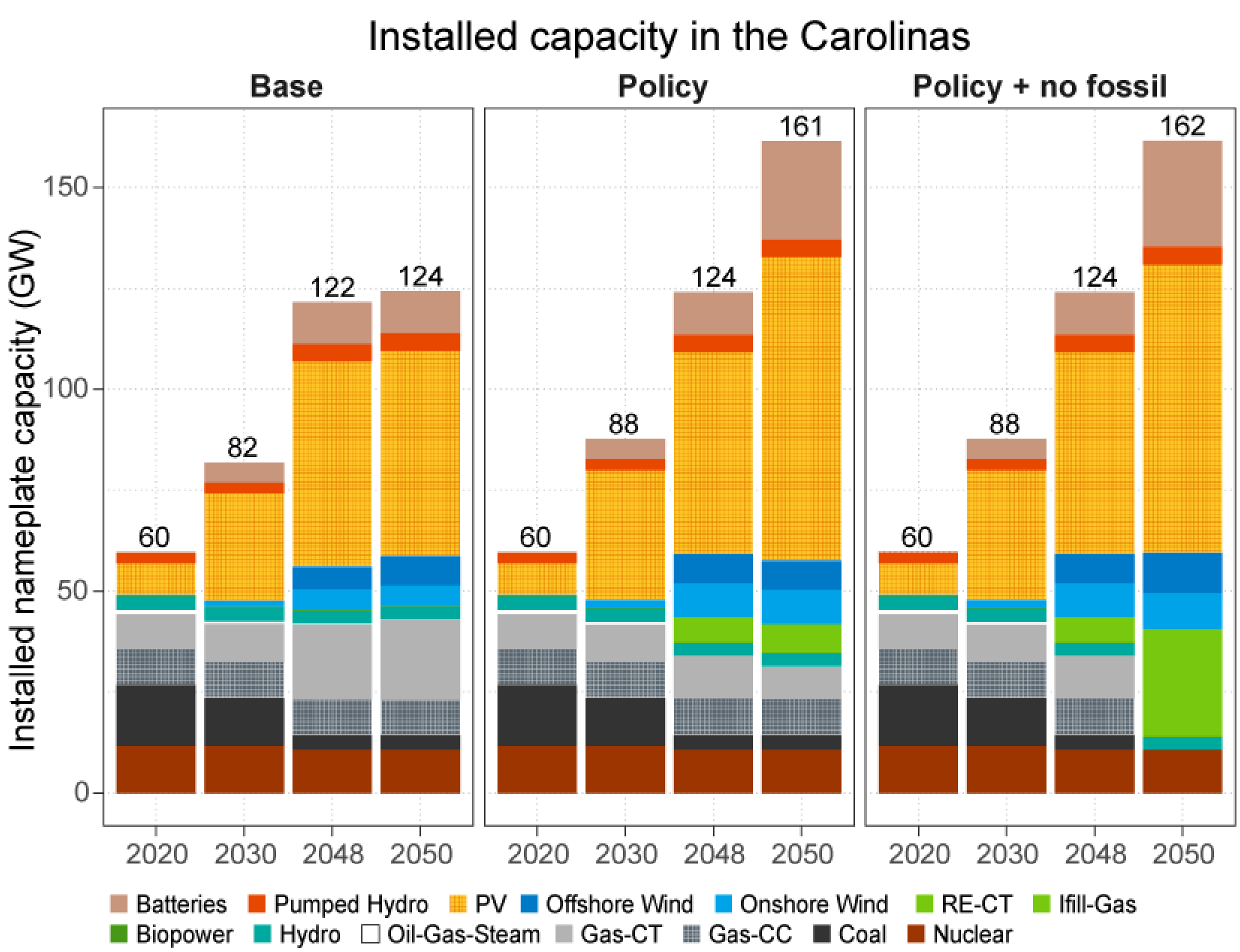
NREL then narrowed down Duke's potential sites for wind and solar to locations that meet key system and decarbonization requirements. For this step, NREL used its Regional Energy Deployment System (ReEDS) capacity expansion model to determine the least-cost resource mix and to identify new transmission scenarios that satisfy critical power system requirements.

For a final validation step, NREL researchers tested the ReEDS resource mix on a full transmission model of the Carolinas using the commercially available PLEXOS software. NREL simulated the proposed buildouts at an hourly resolution, observing how each possibility would play out over one year of operation.

Simulation Results: Gigawatts of New Solar, Wind, and Storage

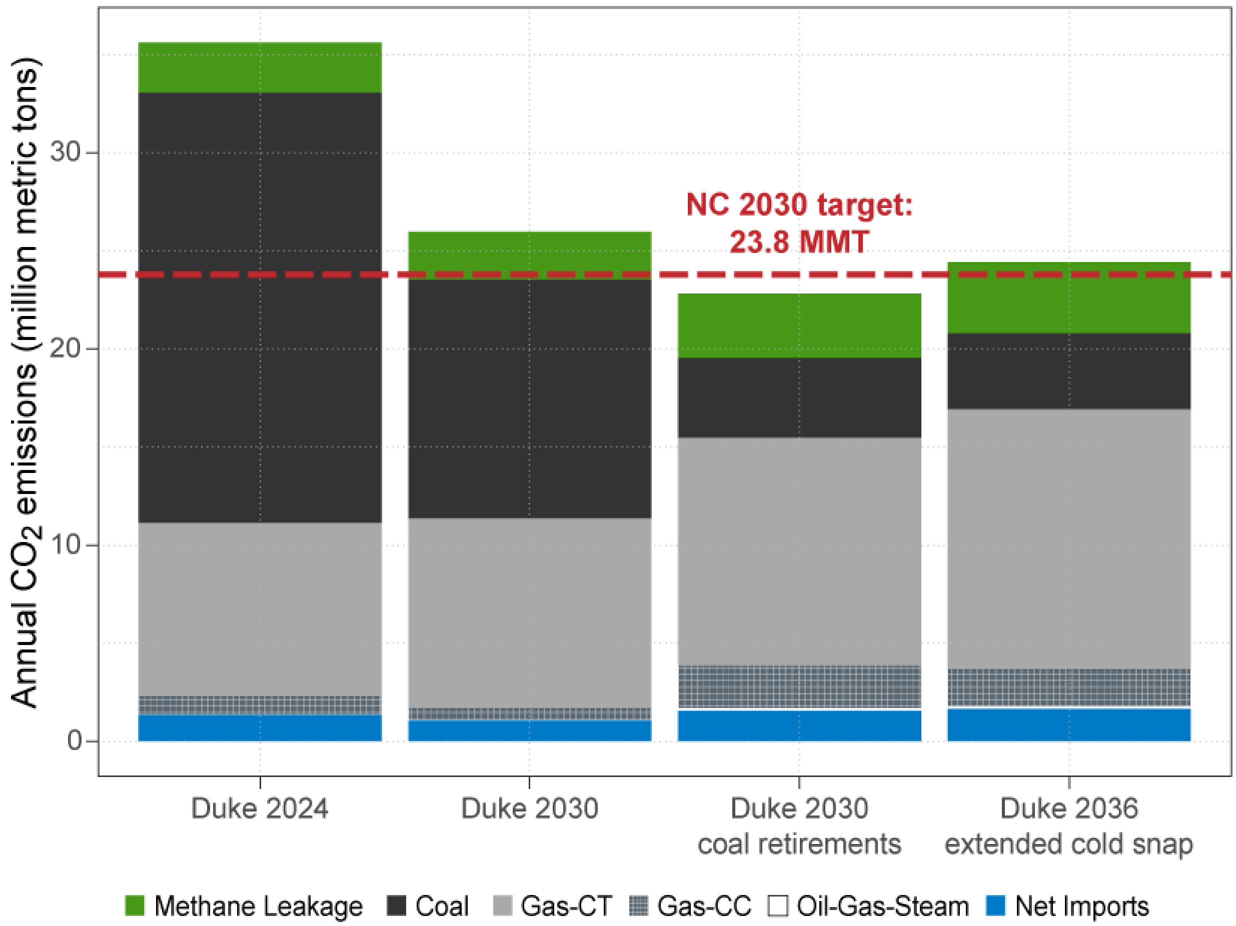
The figure below depicts the generation capacity deployed by ReEDS under a reference case (base) and with the emissions reduction targets of a 70% reduction in North Carolina by 2030 and zero-carbon emissions in 2050 (policy). The policy case also includes a “no fossil” scenario in which all fossil units in both Carolinas must be retired by 2050, including units not in Duke Energy’s service territory.

For its 2030 goals, ReEDS estimates that Duke Energy can meet its 70% target by retiring coal and investing in solar, battery storage, and wind. Although investments in offshore wind and an expansion of existing pumped hydro storage come after 2030, ReEDS does not consider all the logistical constraints for deploying new energy sources, making it important to advance these resources today given the time needed to build and integrate new generation resources.



In pursuit of North Carolina's and Duke Energy's targets for carbon-free energy, NREL modeled scenarios of increasing reliance on carbon-free energy. This figure shows installed capacity for scenarios in 2030 and 2050, given business-as-usual buildout, current policy requirements, and an option that achieves zero fossil-based energy. (RE-CT = renewable combustion turbines; lfill-Gas = landfill gas; Gas-CT = gas combustion turbine; Gas-CC = gas combustion turbine).

In NREL's scenarios, some of the retired coal units are replaced by natural gas generation. This substitution reduces CO_2 emissions overall but increases methane emissions from pipeline leakage. Although pipeline leakage is not calculated in North Carolina's 2030 policy target, NREL measured methane emissions in the scenario analysis, as illustrated in the figure below. Furthermore, emissions can vary depending on the conditions of the system, with lower emissions associated with the planned coal retirements and higher emissions associated with a scenario simulating a more extended winter cold snap.

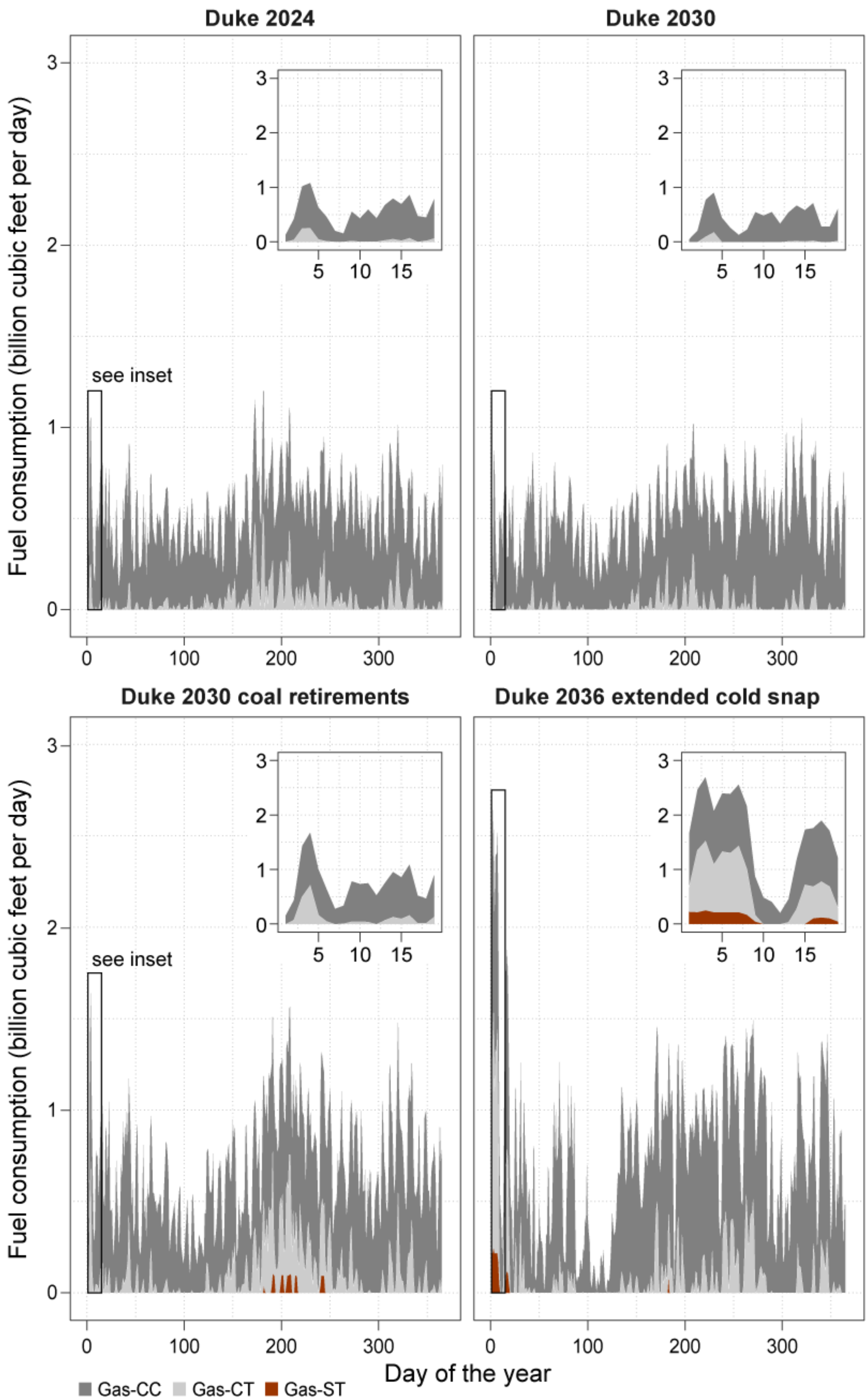


NREL modeled Duke's energy system under a base case scenario (2024) and under different 2030 policy scenarios with various weather conditions. NREL's analysis included emissions from pipeline methane leakage, as well as a scenario that captures a uniquely cold Carolina winter, which adds to carbon emissions.

The difference in emissions based on weather shows the importance of evaluating system operations not only for "typical" weather, but also for more extreme conditions that might stress the system. In the "2036 extended cold snap" scenario, NREL tested the 2036 system buildout against weather data from 2018, a year in which Duke Energy experienced an extended winter peak load event. This cold snap is especially clear in the figure below, in which fuel consumption spikes substantially in the winter months.

"The 2036 extended cold snap modeling is particularly helpful in illustrating the need for technologies that can supply sustained power through challenging winter weather periods," said Mark Oliver, vice president of Integrated System Planning at Duke Energy.

Despite significant amounts of solar PV, wind, and 4-hour duration batteries, replacing Duke Energy's coal plants means finding technologies that can provide energy throughout a multiday winter peak when solar resource is less available and recharging batteries may be difficult. Oliver said that "although natural gas is available to serve this need until better alternatives are available, this could be replaced by hydrogen or renewable biofuels as Duke Energy moves to zero carbon emissions in the future".

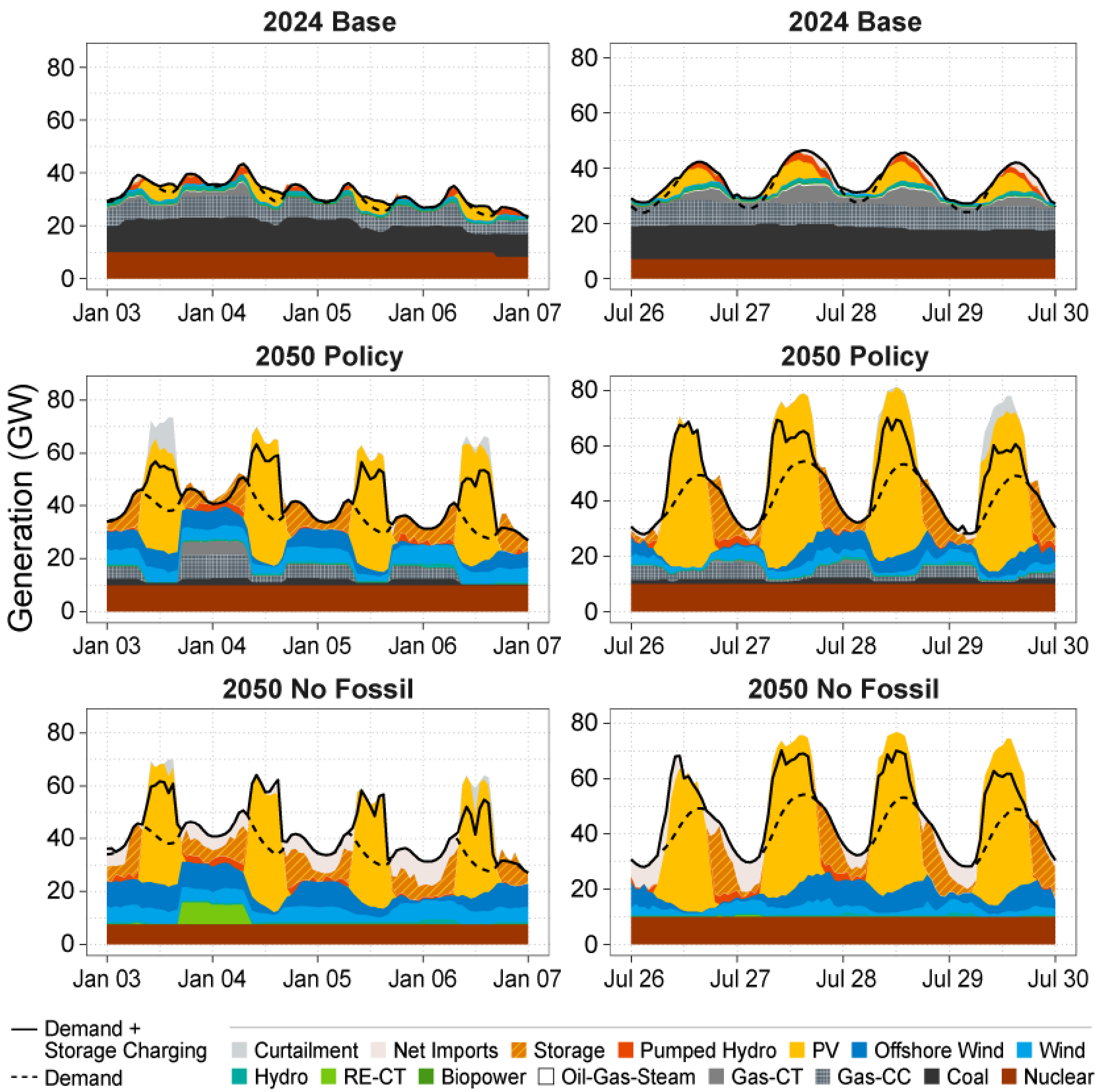

Duke 2024
Duke 2030
Duke 2030 coal retirements
Duke 2036 extended cold snap
Fuel consumption (billion cubic feet per day)
see inset
Day of the year
Gas-CC
Gas-CT
Gas-ST

A graph of daily gas offtakes for each of the scenarios analyzed. The 2036 cold front reveals a dramatic increase in fuel consumption, affecting how Duke can factor in a similarly strong winter for future planning.

Carbon-Free in 2050

The results for 2050 show a diverse system that is generally solar-dominant, smoothed out by storage, and supplemented by nuclear and wind. In the no-fossil case, renewable energy combustion turbines (RE-CTs) serve to provide peaking power toward both the summer and winter peaks. These turbines operate infrequently but are critical for providing power during key moments of high grid stress.

"Having generation resources that can provide energy when called upon during a few critical time periods of the year, when the system is stressed, provides a great deal of value," said Brian Sergi, NREL grid analyst and co-author of the study. Sergi noted that deploying generation technology that operates relatively infrequently but is available at key moments is consistent with other studies looking at the challenges of achieving deep decarbonization, including NREL's recent LA100 analysis exploring pathways to a zero-carbon system for the city of Los Angeles. Although modeled as RE-CTs in this study, this niche could be filled by a range of technologies such as seasonal storage and/or operational strategies like increased imports through coordination with neighbors.



A comparison of winter (left) and summer (right) for 2050 scenarios shows that wintertime will require peaking resources to overcome cold snaps.

The pathway to achieving the zero-carbon target can affect the optimal mix of resources and how they are operated. For example, the no-fossil scenario shows less curtailment due to a greater deployment of storage and a greater reliance on net imports to make up for less natural-gas-based generation, albeit at a higher total cost than the policy case itself. Likewise, pathways in which neighboring utilities also pursue zero-carbon targets reduces opportunities to export otherwise curtailed power, increasing the value of deploying energy storage in the Carolinas.

The study also shows increasing opportunity for interchange with neighboring grids to support balancing supply and demand for the increasingly dynamic system with higher levels of renewable integration. A wide range of sensitivities demonstrate transmission upgrades and builds both within Duke Energy's service territory in the Carolinas and with neighboring power systems, illustrating the robustness of the value of these investments in high renewable outcomes.

An Example for Others

The analysis conducted here identifies a range of pathways for integrating carbon-free resources in the Carolinas. The NREL analysis does not supplant the traditional integrated resource planning effort run by Duke Energy, but it provides additional insight into the challenges and opportunities for achieving a carbon-free system.

The study focused on system buildouts that could meet the emissions reduction targets at least cost primarily from an operational perspective, and accordingly there are additional questions to explore on the path to zero emissions. For example, the projected capacity additions from the ReEDS modeling do not reflect logistical constraints such as speed of interconnection, supply chains, or other limitations that can constrain the actual pace of renewable integration. Realizing the emissions reductions targeted by policymakers and Duke Energy will thus require continued research to understand the challenges and opportunities ahead.

Despite being tailored for the Carolinas, this study can help inform decision-making of utilities, grid operators, and policymakers that are planning for clean energy, not only in the Southeast, but across the country.

Chapter 11. Collaborative Database Maps Lithium-Ion Supply Chain Landscape

Nov. 17, 2022

When charting a course toward a decarbonized future, it is important to understand the existing and emerging manufacturing capabilities for energy storage technologies, such as lithium-ion batteries—the predominant choice for cell phones, laptops, electric vehicles, renewable grid components, and even critical defense applications. Developing a secure supply chain—from material extraction to manufacturing battery cells and packs—is essential for a competitive edge in lithium-ion domestic and global markets.

This "end of life" map generated with data from the Lithium-Ion Battery Supply Chain Database illustrates the significant growth of various lithium-ion battery recycling facility types over one year.

Enter the Lithium-Ion Battery Supply Chain Database, an ongoing collaboration between NAATBatt International and the National Renewable Energy Laboratory (NREL) to identify every company in North America involved in building lithium-ion batteries from mining to manufacturing to recycling. First released in September 2021 and funded by NAATBatt International, this database is the first comprehensive directory of its kind. A recent update in 2022 significantly expands on the database, concluding several months of extensive work by a team of NREL researchers and support from three NAATBatt committees—Manufacturing in North America, Battery Recycling, and Battery Markets.

Establishing a Domestic Battery Supply Chain

Long before powering your electric car, lithium-ion batteries undergo a multistep manufacturing process interlinking separate specialized facilities. Different companies might focus on specific phases of battery development, such as mining or processing raw materials, manufacturing electrodes or cells, and assembling complete battery packs. Currently, U.S. consumers rely on global coordination to maintain a consistent supply of lithium-ion batteries for various applications. The U.S. Department of Energy's National Blueprint for Lithium Batteries aims to change that by instead establishing a domestic supply chain for lithium-based batteries.

"One of the early challenges we identified when assessing the strengths and gaps in the North American lithium-ion supply chain was insufficient data about domestic companies involved in every aspect of battery manufacturing," said NREL Senior Energy

Storage Researcher Ahmad Pesaran. "This database is an initial step in better understanding the lithium-ion battery market and its North American players."

Designing the First-of-Its-Kind Database

To create the Lithium-Ion Battery Supply Chain Database, researchers explored business directories, trade show information, market data, and literature and reports to identify existing companies within the lithium-ion supply chain. The team also performed extensive outreach through direct calls, interviews, and a questionnaire encouraging companies to clarify information about their facilities.

As a result, the database now identifies more than 480 companies and over 560 facilities within North America's lithium-ion supply chain, including mining, material processing, manufacturing, research and development, services, end-of-life management, and product distributors. For each facility, the database lists key information about the company, location, workforce, and products and services. In addition, the database summarizes critical information such as installed battery manufacturing capacity and material production capability, plans for future capacity, types of chemistries and processes, and expansion plans by sector (e.g., transportation, stationary). The updated database also boasts advanced search and mapping capabilities to visualize the evolving market.

"This database brings a unique value to the booming lithium-ion battery market, which is bolstered in part by growing electric vehicle sales," Pesaran said. "We've already received significant interest in this database with more than 800 new downloads from users."

Coordinated Updates Support Industry Growth

NAATBatt and NREL are sharing the complete database with the public, industry, investors, and decision makers to spread awareness of the status of the North American lithium-ion supply chain and promote collaboration to identify strengths, gaps, and potential investments. Continued updates to the database over the next few years will document the growth of the capabilities and facilities across North America.

Chapter 12. National Lab Collaboration Shows Biofuels Are Competitive Alternatives to Petroleum Across the Board

Nov. 10, 2022 | By Anna Squires

Working in collaboration, NREL and several national laboratory partners published comprehensive analyses that uncovered multiple paths to biofuels that will cost-effectively slash carbon emissions in both cars and trucks. *Photo from iStock*

In the race to reduce global greenhouse gas emissions, renewable fuels still carry a high burden of proof: They need to be high performing, efficient, and cost-effective. Now, analysis performed by a collaboration of national laboratory researchers has uncovered a slate of biofuels produced from organic materials, including plants and agricultural waste, that have the potential to replace petroleum-derived fuel.

In two new studies, researchers from the U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL), Argonne National Laboratory, Pacific Northwest National Laboratory (PNNL), and Idaho National Laboratory showed that, together with advanced engine design, biofuels could reduce greenhouse gas emissions by more than

60% compared to petroleum gasoline. On top of that, the biofuels studied could improve fuel performance in cars and trucks, reduce tailpipe emissions, and compete with nonrenewable energy in terms of cost.

Andrew Bartling, an NREL process engineer, Pahola Thathiana Benavides, an energy system analyst from Argonne, and Steven Phillips, a PNNL engineer and analyst, served as lead analysts for two research articles published in *ACS Sustainable Chemistry & Engineering*. The first studied optimal fuel sources and combustion for diesel engines mainly used in freight transportation, while the second paper focused on bioblendstocks optimized for the engines of light-duty vehicles, like cars.

Together, the research studies found multiple paths to cost-effectively slash carbon emissions in both cars and trucks.

“Rather than just focusing on each bioblendstock independently, by studying them simultaneously, we were able to get a bird’s-eye view of the entire field of these fuels,” said Bartling, who helped to lead the techno-economic analysis for both studies. “We were able to identify multiple biofuel candidates that could be cost-competitive with petroleum-derived fuels and could also create significant reductions in greenhouse gas emissions or fossil energy consumption over their life cycles. It’s a win-win from both sides.”

The research was supported by the now-completed Co-Optimization of Fuels & Engines (Co-Optima) initiative, a consortium of nine national laboratories led jointly by DOE’s Office of Energy Efficiency and Renewable Energy, Bioenergy Technologies Office, and Vehicle Technologies Office.

Co-Optima’s work hinged on developing new high-performance fuels that can boost engine efficiency and reduce emissions when combined with advanced combustion approaches. In the biofuels field, this combination approach is critical: While biofuel has significant advantages over petroleum gasoline, engines themselves are also essential to energy efficiency. Designing low-carbon fuels and engines to work together can maximize energy use and vehicle performance.

“We are at the intersection of new innovations in both engines and biofuel,” said Troy Hawkins, Argonne’s group manager for fuels and products and an author on both studies. “Our goal was to develop new biofuels blended with conventional fuels to improve engine performance.”

Finding Viable Biofuel Pathways

In collaboration with Co-Optima’s fuel experts, researchers from all four national laboratories used a screening process to develop a list of biofuels for further study.

"We used specific criteria to narrow many biofuel candidates down to a short list for our research based on the required properties and the engine's combustion mode," Benavides explained.

Then, because converting biomass to biofuel is such a complex process—involving countless variables in feedstock, conversion technologies, and fuel types—researchers from NREL and PNNL conducted a techno-economic assessment of different possible biofuel production pathways, analyzing each pathway for both cost and performance. This kind of analysis, Bartling said, plays to one of NREL's strengths, as the laboratory is considered by many to be world-class in its techno-economic research.

"For each chosen biofuel, we developed an industrial-scale process simulation using thermodynamically rigorous simulation software. Once developed, we were able to figure out what the current cost of fuel production would be, or even what the future cost of production may be as research progresses on things like better catalysts and improved fermentation performance," Bartling said.

Together, the two studies assessed 27 pathways for producing biofuel optimized for different engines. Both studies were consistent: They showed that many of the biofuels were cost-competitive with current gas prices, and most of the technologies performed well. In particular, results from one study's life cycle analysis showed that 10 biofuels have the potential to reduce greenhouse gas emissions by more than 60% compared to petroleum gasoline.

Creating a Biofuel Playbook

One of the most promising aspects of the research, Bartling said, is that it shows the breadth and flexibility of biofuel solutions.

"We found that not only can many of these biofuels be produced cost-competitively but also that there is choice and flexibility in how you design your process, what conversion approach you're going to take, and in the feedstock that you can choose," Bartling said. "Because there is such a variety of fuels, each brings its own performance advantage to the table. And so, not only can we displace a large amount of the fuels produced in the United States with these renewable types of biofuels, but we can also do so sustainably with significant greenhouse gas emission reductions and with the potential to be economically competitive in the market."

These flexible solutions offer a guide for stakeholders to select biofuel pathways that best meet their needs, from efficiency to total ownership cost.

"We provide researchers and industry guidance on assessing biofuels based on a number of complex variables," Benavides said. "The life cycle and techno-economic analysis is important in guiding stakeholders as early as possible. We can't tell stakeholders what choices to make. But these tools can point them in the right direction from the beginning."

Chapter 13. PV Windows Unlock Goal of Increased Energy Efficiency of Skyscrapers

Nov. 18, 2022 | By Wayne Hicks

Researchers at NREL calculated the use of PV windows in Denver could eliminate 2 million kilograms of carbon dioxide emissions annually. *Photo by Dennis Schroeder, NREL*

Skyscrapers dominate city skylines, but these massive glass-walled structures can be made more energy efficient through the addition of thermally efficient photovoltaic (PV) windows, according to an analysis by researchers at the National Renewable Energy Laboratory (NREL).

Their findings, published in the journal *One Earth*, outline building design rules that can yield a structure with net-zero or even net-positive energy consumption.

“There are preconceived notions of what an energy-efficient building looks like, and it usually is not highly glazed, and it probably isn’t very tall,” said Lance Wheeler, a scientist at NREL who specializes in integrating PV technology into windows. “We found that there are other ways to build high-efficiency buildings.”

Wheeler is co-author of the new paper, “Photovoltaic windows cut energy use and CO_2 emissions by 40% in highly glazed buildings,” which he wrote with his twin brother, Vincent, an assistant professor at the University of Wisconsin–Stout. To conduct the analysis, the brothers developed a software called PVwindow that allows users to model the design of PV windows for building simulations.

The other co-authors, all from NREL, are Janghyun Kim, Tom Daligault, Bryan Rosales, Chaiwat Engtrakul, and Robert Tenent.

Buildings account for more than a third of the world’s energy consumption and almost as much of global carbon dioxide emissions. But by combining PV with high thermal performance window technologies, new buildings can become a critical tool in combatting climate change, the researchers noted. Modern office buildings stand out for their looming glass facades, a counterpoint to the days when they were constructed of concrete and single-pane windows. The Equitable Building in New York, for example, has a window-to-wall ratio of 25%. By comparison, the city’s Bank of America Tower opened in 2016, 101 years later, with a ratio of 71%.

The researchers considered buildings with a window-to-wall ratio of 95%—dubbed “highly glazed”—for most of their analysis to clearly illustrate the impact glazing has on building energy performance. Improvements in glazing technologies such as triple-pane windows helped improve the energy efficiency of buildings but so far have not been widely adopted.

“I don't want to sit here and say we should be building highly glazed buildings,” Lance Wheeler said. “We should be building highly efficient buildings. But if we if we choose to keep making these buildings, we’ve got to reconcile their lower performance somehow, and PV windows are one way to do that.”

The researchers simulated the impact of three different types of PV glazing technologies, including NREL’s switchable PV technology. Different glazing technologies were implemented in a building in eight cities, each in different climates. In addition to PVwindow, the researchers also relied on EnergyPlus and OpenStudio software platforms.

With so many windows and sunlight streaming through, highly glazed buildings must expend considerable energy to cool the occupants. PV windows provide thermal insulation for a building and use the absorbed energy to generate electricity. Over the course of a year, the researchers found a clear trend in PV generations in climates with weather that changes strongly with the season. The simulations revealed that in Denver, for example, on-site PV generation can cut in half the day-averaged building electricity load for a heavily glazed 12-story structure. They also determined PV windows in Denver could eliminate 2 million kilograms of carbon dioxide emissions annually.

The simulations showed a step-like increase in performance for each of the three different versions of PV glazing studied and demonstrated reduced energy consumption and carbon dioxide emissions in the eight climate zones.

The researchers found energy use climbs when a building has more windows than wall space. However, the energy use drops when the ratio is increased and includes PV glazing. Indeed, larger floor-to-floor height coupled with PV glazing reduces building energy use. Couple the PV glazing with photovoltaic panels on the outside of the building—particularly facing east and west to capture early morning and late-day sun—and this skyscraper can reach net zero.

“Picture a skyline in, like, New York City where there are these high-rise buildings that are entirely glass,” Wheeler said. “They're fully glazed. The Freedom Tower has millions of square feet of glass. It could be a power plant in itself.”

PV glazing could be paired with rooftop solar to increase the amount of electricity generated, with the potential to create more power than a building needs by using high-efficiency PV windows and unique building geometry, the researchers noted. The transition could address climate changing goals without sacrificing the architectural freedom of highly glazed facades.